1. Overview

The use of renewable energy is an important target for environmental policies in many countries around the world. The expected impacts of climate change has foster investment and research on clean power generation that results in lower levelized costs for some renewable energy technologies, mainly wind power generation (IRENA, 2017). As a consequence, the participation of wind and solar power generation in power grids has grown steadily for the past years (IRENA, 2016). More recently, the complementarity of wind power generation and hydropower plants has been the subject of research in many different countries. In general, hydroelectric generation has features that contribute to the expansion of renewable sources such as wind and solar - known by their variability (Acker et al., 2011). The hydropower can store energy through reservoirs, are flexible and has low operation costs. Thermal generation shows only one advantage, they are predictable – exactly because it does not rely on variable renewable sources. This research tested the limits of wind-hydro integration for the Brazilian power grid, as it is extremely dependent on hydropower plants (more than 60% of installed capacity) and has presented a great increase in wind power generation in recent years. In order to achieve our objective, we simulated the operation of Brazilian grid – in 2020 and 2030 –, comparing a baseline scenario (EPE, 2015; IEA, 2013) with a scenario with maximum wind power penetration that has similar installed capacity.

Our results show that it is not possible to have a reliable power system just counting on wind, solar and hydro power plants. The use of thermoelectric generation plays an fundamental role to provide energy, mainly, in the second semester, when major run-of-river hydro plants in Amazon present low water inflows. The problem that arises is how to establish a price incentive to foster thermal power investment in a market dominated by low marginal cost sources that push electricity prices down.

Keywords – Wind integration; Thermoelectric investment; Variability; Flexibility.

1. Introduction

Global warming is one of the most challenging issues of the 21st century. The latest climate forecasts compiled by the Intergovernmental Panel on Climate Change (IPCC, 2013) point to a very different future from the reality in which we currently live. Impacts on biodiversity, food security and coastal areas - where much of humanity lives - are some of the situations that may occur by the end of this century. Extreme weather events tend to become more frequent and intense. The most accepted hypothesis to explain these climatic changes is human action, through the emission of greenhouse gases and the destruction of natural ecosystems in their various economic activities (IPCC, 2013).

The solution to this problem is complex, since it requires a coordination between all countries on the planet. The major greenhouse gas emitting countries have different stages of development, and a commitment that articulates current responsibility with historical responsibility has been a barrier to reaching a definitive agreement. In addition, the supply chain of almost every good and service offered today uses fossil fuels in some stage. Investments in the extraction and refining of fossil fuels represent a significant percentage of assets in world economy. By 2015, five out of the 25 largest global companies are in the oil industry (CHEN, 2015). The technological lock-in effect for the coming decades is great, making the transition to a low carbon economy a difficult task to achieve at the levels required to limit the most intense effects of climate change (IEA, 2015).

However, some mitigation strategies became successful in recent years. The expansion of power generation through low-carbon renewable sources is a reality in many countries - notably China, the European Union and the United States (IRENA, 2016). In 2015, $150 bn were invested in these technologies (ECONOMIST, 2017). One of the technologies that emerges as the most successful case is wind power generation. After a period of support - through public policies such as exclusive auctions, subsidy for research and feed-in tariffs, wind power generation can already compete with traditional sources of power generation (IRENA, 2017).

The penetration of wind power sources into electrical systems as a climate change mitigation strategy presents new challenges for the planning and operation of power grids. Wind sources have a component unwanted of short-term unpredictability and oscillation that affects system’s reliability (IPCC, 2012). While modest progress has been made in electricity storage technologies (batteries, air compression, hydrogen, among others), the integration of
wind power sources with other traditional sources of power generation had succeeded in foster clean energy penetration (IRENA, 2016). The greater the flexibility and predictability of the generation sources integrated to wind power generation, the safer the electrical system becomes (Bird et al., 2016). In this sense, hydroelectric systems with reservoirs are interesting candidates to perform the balancing function of wind power generation. Hydroelectric generators are remarkably flexible when compared to thermal generation technologies (Acker et al., 2012). Brazilian grid uses hydropower plants to provide 65-90% of its power supply. Many of these hydro plants has storage capabilities. Thus, it is an interesting case study for wind-hydro integration. Our research focus in understanding the limits of this integration and what role fossil and biomass-fueled thermal generation plays to balance the system, providing reliability to power supply.

2. Background
The academic community has closely monitored the integration of hydro and wind sources since the early 2000s, resulting in the organization of an Expert Meeting by the International Energy Agency in December 2003. After this meeting, IEA established a research and development task on wind-hydro integration in power grids (Acker et al., 2012). Despite relying solely on case studies in developed countries, task force’s efforts influenced other researchers, which expanded the research to developing countries like Mexico, India, China, South Africa and Brazil (Jaramillo et al. [2004], Karki et al. [2010], Wang et al. [2013], Gebretsadik et al. [2016]). In Brazil, preliminary studies (do Amarante e al. [2001], Pimenta and Assireu [2015], Schmidt et al. [2016a], Schmidt et al. [2016b], and de Jong et al. [2016]) have indicated a temporal complementarity between the generation capacity of hydropower plants and wind - as the greatest potential for wind power generation occurs in the months of the lowest water flows in the main Brazilian basins, as shown in Figure 1. In that sense, this complementarity may be able to reduce investments in thermal sources, resulting in a more renewable and low carbon system than today.

![Figure 1. Wind Generation Factor x Hydro Plants Natural Flow Rates in Brazil](image)

The effects of wind-hydro integration on thermal generation were also studied by these authors, in order to identify positive and negative effects on grid’s optimization. Kiviluoma and Holttinen (2006) and Kiviluoma et al. (2006) studied the penetration of 10%, 20% and 30% of wind power generation in the Nordic electrical system. The model proposed by the authors did not deal with the shutdown of old power plants and - in this way - did not present balancing difficulties due to the high penetration of variable sources. However, the high penetration of wind power in a hydroelectric dominated system would reduce the spot price of electricity, creating challenges to attract new generation investments into the system. For the authors, it is not clear whether a generator system with these characteristics could be derived from a free market model in the electric sector - even though it is the most cost-effective way to supply the electricity demand.

Wang et al. (2013) developed a particle swarm optimization (PSO) algorithm for the coordination of wind-hydrothermal integration, based on the concept of hydro plants balancing wind power generation. The authors tested the algorithm using data from the grid of northeastern China on a representative 24 hour horizon. This system has 63 thermal generators with a total capacity of 11,750 MW and three hydroelectric plants totaling 2,000 MW. Six wind farms were simulated for integration into the current system with installed capacity varying from 1,300 MW to 200 MW. With the penetration of wind power generation, the distance between maximum and minimum generation in the thermoelectric plants increases, even though the thermoelectric generation remains constant for long hours in a row. During most of the analyzed period, hydroelectric generation was able to balance the variability of wind power sources, but for two hours the decrease in wind power generation combined with the increase in the load

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1 Monthly average for 25 hotspots in Brazil using Soria et al. (2016).
caused a significant increase in thermoelectric generation - which after that period had to shut down again to levels near the start of the ramp up cycle. As a result of the model, the authors found that fuel costs for generation fall with the greater penetration of wind energy sources. The authors also infer that wind penetrations higher than the balancing capacity of hydroelectric plants must respect the optimization of the operating costs of thermoelectric power plants, since the large variation of wind power generates higher costs in the thermoelectric generation (start-up costs and loss of efficiency) that may outweigh the drop in fuel purchase costs and result in overall higher generation costs.

Gebretsadik et al. (2016) developed a method of analysis for optimum penetration of wind power generation based on the creation of short and long term goals for the use of hydroelectric reservoirs in order to balance the entire system of the country. South Africa plans to invest in a large expansion of wind power by 2040, increasing its share to 20% of installed capacity (23,000 MW). The results of the model indicate that using the reservoirs as 100% of the back up to balance the wind power generation is not the best option for the system, since it increased the unmet demand during the analysis horizon. The simulated operational data - hourly optimization for 24 hours in four significant stations - indicate that there is potential for a penetration of 18.69% of installed wind power capacity in South Africa, considering the current conditions of the generating system. This would be possible with the implementation of a new management model for reservoirs in the Zambezi River Basin, which would fulfill the role of batteries for wind power sources, which in turn would increase the reliability of both hydroelectric generation and wind power generation. The use of hydroelectric plants for this balancing function would also provide a better use of coal-fired power plants (a major component of the South African grid) that - not needing to keep up with peak variations - would operate more efficiently.

Schmidt et al. (2016b) have used an optimization model to evaluate the expansion of Brazilian electricity generation in two different scenarios. In the first, the model can choose between a mix of renewable energies to execute the expansion (run-of-river hydro plants, wind and solar PV). In the second, the model must carry out the generation expansion in a more conventional way, with the use of run-of-river hydro plants and thermoelectric plants. After optimizing the expansion, an operating model was used to check how the system operates. In the first scenario, the authors stated that the higher the penetration of renewable energy generation, the lower the total dispatch of thermoelectric plants. Under these conditions, no thermoelectric generation is used on a regular basis and the reservoirs are able to balance generation variability in the daily average. Whenever there is a condition of low natural inflow in hydroelectric plants, thermoelectric generation grows significantly to preserve the supply of electricity. The curtailment of renewable energy occurs mainly in the early years of the simulated period, since there is a large installed capacity of hydroelectric plants in relation to total load. In the conventional expansion scenario, the authors found a regular thermal dispatch, as hydroelectric generation suffers from the seasonality of natural inflows, a situation aggravated by the installation of plants without reservoirs in the Amazon. There is also a greater curtailment since the correlation of generation potential between new hydroelectric plants and those already installed is large - and certainly higher than that of other renewable sources. The difference between the use of thermoelectric plants in the two scenarios can be demonstrated through the 100% higher dispatch in the conventional expansion scenario. Also, the thermoelectric generation capacity reaches - at most - 15% of the maximum demand in the scenario of renewable expansion, while this value reaches 40% in the other scenario. However, the renewable expansion model was more robust and stable than conventional one. In the climatic extremes scenarios, renewable expansion presented 0.2% of unmet demand while the value reached 1% for conventional expansion - even if the increased thermal back up of the second scenario.

As we can see, the literature has presented several impacts from wind-hydro integration on thermal generation. Mostly, it reduces significantly the dispatch of thermal units with positive effects on fuel costs. However, there is a negative feedback as thermal generation dispatch becomes more variable, producing inefficiencies that could cancel the positive effect. Also, with higher penetration of low marginal costs technologies, prices decreases and may not able to attract new investment in thermoelectric units.

3. Brazilian wind penetration model

Our research aims to understand the impact of wind-hydro integration in thermoelectric generation and investment in Brazil. To accomplish our goal, we simulated several scenarios for maximum wind power penetration. We choose PLEXOS (ENERGY EXEMPLAR, 2016) as simulation tool, because of its ability to model complex hydropower systems.

3.1 – PLEXOS and optimization schedule

PLEXOS is a computer program developed by the Energy Exemplar Company and is one of the most widely used energy simulation tools in the world. The tool is based on mixed integer linear programming to determine the solution that minimizes generation costs - among many other configuration options - and has already been used in
numerous scientific articles in the power sector (Foley et al., 2012; Deane et al., 2012; Deane et al., 2014; Shirley and Kammen, 2015).

PLEXOS allows the description of an electrical system as a set of objects - which belong to specific collections according to their role in the sector. For each of these objects, PLEXOS associates properties with the intention of simulating all the characteristics of these objects. A root file represents an electrical system, in which each object is inserted as part of that system. The objects are grouped into classes that bring together similar characteristics between different objects, such as generators, fuels, reservoirs, rivers, transmission, among others.

For this research, we used PLEXOS two-stage optimization model, as a medium-term schedule was established in a three-year horizon (2019-2021 and 2029-2031) and weekly optimization to set targets for reservoirs volume, and a short-term schedule simulated the grid operation in a one year horizon (2020 and 2030) and 4-hour optimization process. This procedure is important to simulate the way Brazilian authorities dispatch hydro plants – considering long-term value of the water – that would not be captured in a single short-term schedule.

3.2 – Simulation model and Scenarios

Changes in the relationship between storage capacity, water inflows and power demand are fundamental variables to establish the penetration limit of variable renewable sources.

The years 2020 and 2030 were chosen for the analysis, as it allows us to check the impact of demand growth (EPE, 2016; Soria, 2016) – Table 1 – and planned hydroelectric expansion (SAE, 2015) – which, in Brazil, will notably increase the installed capacity of the system but does not increase the volume of reservoirs.

In the last decade, there were four major vectors of supply expansion to meet the growth of load: hydropower plants, biomass-fueled thermoelectric plants, natural gas thermoelectric plants and wind turbines. Hydroelectric generation capacity increased by 14,361 MW, compared to 9,555 MW of biomass-fueled thermoelectric plants, 8,926 MW of fossil-fueled power plants and 7,396 MW of wind power. Other significant sources were the small hydroelectric plants (3,611 MW), which contributed to hydropower generation as the major part of the Brazilian expansion in the period. Most of Brazilian major hydropower investment projects are run-of-river plants situated in Amazon.

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy Demand (GWh)</th>
<th>Peak of Demand (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>662.719</td>
<td>98.078</td>
</tr>
<tr>
<td>2030</td>
<td>840.472</td>
<td>124.384</td>
</tr>
</tbody>
</table>

The information necessary to model each hydropower plant in Brazilian grid was listed in PDE 2024 NEWAVE files (EPE, 2015). For thermoelectrical units, we used the information presented in IEA (2014), Soria (2016), Miranda et al. (2016), Deane et al. (2015), Irena (2015), EIA (2013) and Eletrobrás (2016). For fuel prices, we considered the data presented in CCEE (2016), EPE (2015), UDOP (2016) and IEA (2015).

We also modeled different scenarios for the water inflow in the reservoirs. The monthly average flow data for each plant were also taken from the PDE 2024 NEWAVE files (EPE, 2015). This file describes the historical series of natural inflows of all plants installed or planned between the years 1931 and 2013.

To determine the time interval that would be extracted from the 1931-2013 historical series and used in our model, we calculated the average annual flow of all the plants in the system (installed and planned) and, subsequently, the average of a seventeen-year interval. Comparing the average of these seventeen-year intervals to the average for the entire period 1931-2013, we chose the interval closest to the average of 1931-2013 and called it “Medio” (mean). Also, we chose the interval with the lowest average and called it “Seco” (dry).

The baseline scenarios were established using planned installed capacity for 2020 and 2030, using the information from EPE (2015) and IEA (2013), as shown in Table 2.

<table>
<thead>
<tr>
<th>Source</th>
<th>Installed Capacity 2020 (MW)</th>
<th>Installed Capacity 2030 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>107.124,10</td>
<td>138.724,80</td>
</tr>
<tr>
<td>Small Hydro</td>
<td>5.706,05</td>
<td>8.467,30</td>
</tr>
<tr>
<td>Solar PV</td>
<td>976,70</td>
<td>2.942,10</td>
</tr>
<tr>
<td>Biomass</td>
<td>11.938,95</td>
<td>13.595,60</td>
</tr>
<tr>
<td>Fossil</td>
<td>27.966,74</td>
<td>36.551,26</td>
</tr>
<tr>
<td>Wind</td>
<td>17.300,10</td>
<td>33.150,10</td>
</tr>
</tbody>
</table>
The first attempt to optimize Wind scenarios – as we called maximum wind power penetration scenarios - were carried out with a 100% renewable system - hydroelectric, solar, biomass and wind power (except for nuclear plants). To achieve this set-up, we substitute fossil-fueled thermoelectric generation with wind power generation, following Soria (2016) hotspot technique.

As demand deficits were identified, the thermal / wind substitution process was partially reversed until a configuration that did not generate a deficit in both the medium term (3 years, weekly) and the short term (1 year, every four hours) was did not present any deficit. This reversal also considered the relationship between capacity factors of the different technologies resulting from the Baseline optimization. Where higher wind power capacity factors were found in relation to non-renewable thermoelectric plants, the replacement of technologies followed the 1 MW installed wind power for each 1 MW installed thermoelectric plant rule.

Brazil has an interconnected system with several nodes. We used the information in EPE (2015) to model transmission between these nodes, as transmission is also a key element in variable renewable energy penetration (Miranda et al., 2016; Bird et al., 2016; Purvins et al. 2012). Figure 2 present an illustration of the different scenarios.

4. Results and Discussion

4.1 – Wind power penetration and thermoelectric generation

Our results show that Brazilian hydro plants’ reservoirs can balance a great amount of wind power variability. For every Wind scenario, it exceeded the installed capacity of the baseline scenarios in 2020 and 2030. In that sense, the planned expansion of wind power presented in EPE (2015) and IEA (2013) does not utilize all the potential that wind-hydro integration can deliver to Brazilian grid. In 2020, the baseline scenario present 6,47% of wind power generation. The Wind Medio scenario – maximum wind power penetration with regular water inflows – shows 11,47% of wind power generation and the Wind Seco scenario – maximum wind power penetration with lower water inflows – shows 11,26%. In 2030, similar results can be seen, as baseline scenario presents 9,79% of wind power generation against 13,26% and 13,12%, in Wind Medio and Wind Seco scenarios, respectively.

In the other hand, fossil-fueled thermoelectrical generation falls considerably as more wind power generation is used to supply power to the system and there are no changes in water inflows. Thermal generation participation drops from 10,37% in the baseline 2020 scenario to 6,06% in Wind Medio 2020 scenario. In 2030, it drops from 6,86% in baseline 2030 scenario to 4,87% in Wind Medio 2030 scenario. When we look to the scenarios with lower inflows to the reservoirs, we can see that thermoelectric generation has an important role to balance the system, as it covers the reduced generation from hydropower plants – specially run-of-river plants in Amazon. Wind Seco 2020 presents a thermal participation of 8,04% and Wind Seco 2030, 8,22% - even higher than baseline 2030 scenario.

We must consider that, even in Wind Medio scenarios, fossil-fueled thermal generation has an important role to balance the system, avoiding loss of load. This is especially true in the second semester, when natural water inflow is lower in the Amazon basin and run-of-river hydro plant cannot cope with generation requirements (Figure 3, 4 and 5).
Table 3. Participation of Wind Power and Fossil-Fueled Thermal in total Generation in different scenarios

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Wind Medio</th>
<th>Wind Seco</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>Thermal Fossil</td>
<td>10,37%</td>
<td>6,06%</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>6,47%</td>
<td>11,47%</td>
</tr>
<tr>
<td>2030</td>
<td>Thermal Fossil</td>
<td>6,86%</td>
<td>4,87%</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>9,79%</td>
<td>13,26%</td>
</tr>
</tbody>
</table>

Figure 3. Power Generation by technology in Baseline 2020 and Wind Medio 2020 scenarios

Figure 4. Power Generation by technology in Baseline 2030 and Wind Medio 2030 scenarios

Figure 5. Power Generation by technology in Wind Seco scenarios

4.2 – Thermoelectric plants capacity factor

The months of September, October and November (also December in the scenarios of lower inflows) presented a great deficit of renewable energy when running maximum wind power penetration scenarios — being fully compensated by fossil-fueled thermal generation. During the second half of the year, the inflows in Brazil (with the exception of the South) declines considerably. Without large reservoirs, the new large hydro plants installed in the Amazon contribute less to the national energy supply. Even with the increase in the average generation of wind farms in the Northeast and South Brazil, the hydroelectric plants with reservoirs are not able to balance the power
system. This situation is even worse when we take into account that the increase in the average generation of wind power plants is also associated with a greater variability (in absolute terms) of their generation (Figure 6). Thus, the dispatch of thermoelectric power plants is fundamental to offset both the seasonal variation of hydroelectric power generation in the Amazon and the increased short-term variability of wind power generation in the various hotspots in the country.

As we go deeper into the model’s results, we can see that the major difference between the Wind Medio and Wind Seco scenarios is not in the annual capacity factor of these thermoelectric plants— that is obviously greater, but in the amount of optimization periods (4-hour period) with critical use of the thermoelectric system (greater than 80% of the maximum power generation possible). In 2020, at the same time capacity factor increase 15%, critical use of fossil-fueled thermal generation increased 63%, between Wind Medio and Wind Seco. In 2030, capacity factor of fossil-fueled thermal units increased 18%, when critical use increased 57%.

This result was expected, as thermoelectric plants are driven primarily in critical periods of the second half, operating at very low rates at other times of the year. Table 4 presents this data.

<table>
<thead>
<tr>
<th>Capacity Factor (annual average)</th>
<th>2020 Wind Medio</th>
<th>2020 Wind Seco</th>
<th>2030 Wind Medio</th>
<th>2030 Wind Seco</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical periods</td>
<td>471 / 2.196</td>
<td>770 / 2.196</td>
<td>208 / 2.190</td>
<td>327 / 2.190</td>
</tr>
</tbody>
</table>

4.3 – Final remarks

After the optimization model, we can clearly see that - despite the increase in wind power generation (and average wind speed) in the period of lower hydroelectric power supply - the variance in wind power generation also increases in the second semester. Thus, just when it is most needed input capacity from the hydraulic sources to cover the intermittency of wind power generation, there is not enough hydro generation, even considering the large storage capacity of the Brazilian reservoirs. Mainly in the last quarter of the year, there would be a deficit in the national power generation - with unmet demand mainly in areas with higher wind power generation.

The expansion of hydroelectric projects in the Amazon region - a region which still has untapped potential - highlights the need for investment in thermal power plants to provide resilience to the Brazilian grid. Amazon hydropower plants suffer great difficulties on their environmental licensing and, in most cases, cannot rely on reservoirs that could mitigate the large variability in their generation capacity throughout the year, adopting run-off-river technology. The Belo Monte power plant is a striking example of the inability of new Amazon hydropower plants to provide energy to cover the variations of wind power generation.

Thus, we can conclude that even if there is a significant investment in wind power and hydropower plants in the Amazon as a strategy to reduce GHG emissions in the Brazilian electric sector, it will be essential we follow this strategy with investments in thermal power plants capable of providing resilience to the system. The nature of these thermal power plants and their impact on climate change will depend on market conditions and public incentives created to support the adoption of cleaner technologies and fuels.

Considering low-carbon alternatives, Brazil should explore its potential for biomass-fueled thermoelectric generation, as it can be an interesting substitute for fossil-fueled thermoelectric sources and the Amazonian hydroelectric plants themselves. An operating strategy that uses this technology as base load power plants can increase thermal generation efficiency, while allowing a freer management for existing hydroelectric reservoirs.

Considering low-carbon alternatives for power generation, Brazil should explore its potential for biomass-fueled thermoelectric generation, as it appears to be an interesting alternative to replace fossil-fueled thermoelectric sources and even the Amazonian hydropower plants themselves. An operating strategy that uses this technology as base load power plants can increase thermal generation efficiency, while allowing a freer management for existing hydroelectric reservoirs. According to PNE 2030 (EPE, 2008), agribusiness waste could reach 1.5 million bep / day in 2030. This level is almost three times higher than that recorded in 2005 of 590 thousand bep / day. Brazil has sufficient climate and areas for agriculture to maintain the expansion of biomass production (SCOLARI, 2006), as guarantee the expansion of these sources of energy. Electricity in the grid (EPE, 2008).

The main problem is how to design a price mechanism capable of foster investments in thermal generation of any kind when low marginal cost technologies dominate power generation and push energy prices down. According to Frondel et al. (2010), the profit of four German major electricity producers lowered by 20% when renewable
energy (mainly wind and solar) became popular in the country and producer prices decreased 8%. At the same time, consumer prices increased by 3% as public policies subsidize the penetration of these renewable sources. Imagining that renewable sources could reach 100% of a grid generation, energy prices would be close to zero, deterring all new investment that was not completely subsidized. Governments and the energy industry ought to rethink their policies in order to adequate themselves to this new reality of high renewable generation penetration. Flexibility and reliability of power generation should be paid appropriately to develop a resilient power system. Subsides must be redesigned to couple with the increasing risks of lesser investment by higher costs thermal generators that provide security to the grid.

5. Conclusion
Renewable energy has become an important part of national grids. It is a fundamental strategy to mitigate global warming and it has benefit from governmental subsides that has foster its participation on power supply worldwide. Brazil has a singular power system – with great participation of hydropower plants with reservoirs – that can be very useful to allow wind and solar power penetration. As hydro plants are extremely flexible and have low marginal costs, wind-hydro integration has been subject of several studies and it can help the development of new renewable energy generation.
Our study used PLEXOS to simulate high penetration of wind power generation in Brazil, and our results shows that wind-hydro integration has a great potential to balance wind power penetration in the country. In 2020, wind power generation could be the double of what has been planned by Brazilian authorities. Nevertheless, thermal power generation will be necessary to guarantee a safe power systems as hydropower plants faces lower water inflows in the second semester, the exact same time when wind power generation present its highest variability. Also, there will be years with drier conditions that the power system would count even more on thermal power generation. Though, the use of thermal power generation to supply peak load is not optimal as thermal technologies are not flexible enough and has more tight parameters to operate efficiently than other sources. Low marginal costs of renewable power generation have been pushing producer prices down, halting investment in conventional thermal generation. As old units are retired, there is an increasing risk to the system reliability and safety, because thermal power generation provides important back-up services to renewable sources. It is crucial to find new policies that can integrate the effort to mitigate climate change and – at the same time – do not increase loss of load probability in power systems around the world.

6. References


